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Compound heatwave and drought hotspots and their trends in Southeast Australia

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Abstract

Compound extreme natural events cause a significantly larger impact than individual extreme events. Therefore, the urgency of exploring the climatology of compound events is growing. This paper is aimed to identify the current hotspots of compound heatwaves and droughts (CHD) and trends in their occurrence in southeast Australia. In this context, 61 weather stations were selected from the study area, and analyses were carried out over the extended summer season of the time period 1971–2021. The hotspots of CHDs in southeast Australia were identified considering both the total count of CHD days and 90th percentile of CHDs during the study period. The study period was divided into two periods 1971–2000 and 2001–2021, to assess the change in hotspots spatially and temporally. Four different attributes of CHDs based on the number, duration, severity and amplitude of CHDs were also calculated, and Mann–Kendall (MK) test followed by Sen's slope was adopted to detect the trends in all these four attributes of CHDs. Trends in CHD indices were also calculated for the two periods of 1971–2000 and 2001–2021. For calculating the CHD, excess heat factor (EHF) was used to identify the heatwaves. In the case of drought identification, SPEI and SPI drought indices were adopted with aggregation of 3 and 126 antecedent months, and three different threshold values were selected to consider three levels of dry conditions, e.g. 0, −0.5 and −1.0. It has been found that more CHDs occurred on the eastern side of NSW and Queensland states. Furthermore, the total count of CHD days increased notably during the last two decades. The trends in CHD indices were found to be significant in the recent period (2001–2021), and there was no trend in the earlier period (1971–2000). The findings of this study will help to plan heat and drought-related emergency management in the study area.

Keywords Compound events · Drought · Heatwave · Southeast Australia · Trends

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1 Introduction

An increase in global mean temperature has been shown to trigger the increase in frequency and intensity of various climate and weather-related extremes, such as droughts, floods, rainfalls and heatwaves (Cowan et al. 2014; Reddy et al. 2021). Numerous recent studies projected an alarming increase in these extremes in future (Dosio et al. 2018; Naumann et al. 2018). Recently, this increasing tendency of weather extremes around the world is also acknowledged in the Sixth Scientific Assessment Report published by the Intergovernmental Panel on Climate Change (IPCC 2021). Similar to the rest of the world, Australia has also been facing extreme and more frequent weather extremes (Institute of Foresters of Australia and Australian Forest Gr 2020) and continuous research works are being carried out to better understand and explain these extreme events (Gissing et al. 2022; Perkins 2015; Ridder et al. 2022a).

A heatwave is characterised as an unusually high temperature that continues for several days. However, the methods for defining heatwaves vary considering the relative threshold and/or absolute threshold methods depending on the geographical locations around the world (Baldwin et al. 2019; Mukherjee et al. 2020; Shi et al. 2021a, b). Heatwaves have been occurring more frequently and causing severe impacts on agriculture, power plants, weather and, more importantly, human health. Heatwave is the deadliest natural hazard in Australia and has disastrous impacts on economic productivity and human health, even leading to human deaths (Coates et al. 2014; Zander et al. 2015).

Drought is also considered to be another crucial natural hazard that occurs almost all over the world and is defined as a prolonged deficit of precipitation. Different indicators have been utilised over the years to identify drought conditions considering different input parameters, e.g. precipitation and temperature (Mishra & Singh 2010; Vicente-Serrano et al. 2010). Drought also caused adverse impacts on health and socio-economics, including livestock, hydropower production, energy consumption and food production (Greve et al. 2014; Hao et al. 2014). Due to major influence of drought on society, researchers have been investigating droughts occurring around the world, including Australia (Shao et al. 2018; Trenberth et al. 2014). It is also evident from the literature that the risk of drought is increasing due to climate change (Wu et al. 2019).

Undoubtedly, study on the individual extreme event, such as heatwaves and droughts, provides insight into their mechanism and impacts. However, studies showed that people around the world are likely to expose to multiple weather extremes at the same time (Dilley et al. 2005; Institute of Foresters of Australia and Australian Forest Gr 2020) and hence it is recommended to analyse multiple weather extremes concurrently. Moreover, the probability of occurrence of more than one weather extreme at the same time at the same place is also increasing (Forzieri et al. 2016; Mazdiyasni & AghaKouchak 2015; Zscheischler et al. 2018). In the literature, when two or more weather extremes occur concurrently in the same region, it is referred to as a compound event or hazard (Leonard et al. 2014; Messori et al. 2021). Compound events cause more damage to human health and socio-economic system compared to individual weather extremes (Hao et al. 2021; Zscheischler et al. 2018). It is evident that univariate analysis of individual weather extreme is not sufficient and this underestimates the impact of potential combinations of weather extremes (Leonard et al. 2014; Zscheischler et al. 2020). Therefore, concerns and needs have been growing to examine the compound events in recent years all over the world (Raymond et al. 2020; Sutanto et al. 2020; Zscheischler et al. 2020) including Australia (Ridder et al. 2022b).

Increase in droughts and heatwaves has been experienced all over the world, including Australia, and is projected to become more frequent and intense in the future (Alizadeh et al. 2020; Wu et al. 2021; Zscheischler et al. 2020; Yildirim and Rahman 2022a). Recently, compound heatwaves and drought (CHD) have been considered as one crucial compound event (Mukherjee et al. 2018; Sutanto et al. 2020; Zscheischler et al. 2018). An exacerbated negative impact of CHD on human health, agriculture, energy and the socio-economic system has been reported (Liu et al. 2020; Sutanto et al. 2020).

Temperature, precipitation and soil moisture are connected based on a process-level interaction loop (Miralles et al. 2019; Zscheischler & Seneviratne 2017). Consequently, heatwaves and droughts are likely to occur simultaneously (Berg et al. 2015; Ukkola et al. 2018) and should be examined as compound events rather than individual ones (Zscheischler and Seneviratne 2017). Although the durations of drought and heatwaves are different (Miralles et al. 2019), the possibility of joint occurrence of drought and heatwaves plays a crucial role in natural hazard assessment in Australia similar to other countries (Ridder et al. 2022a).

Since precipitation, temperature and soil moisture vary over different regions, the spatial distribution of compound heatwaves and droughts is also heterogeneous in nature (Konapala and Mishra 2020). Therefore, it is vital to assess the occurrence and trend of the compound heatwave and drought quantitatively. CHD has been quantified based on different indices, including frequency, duration, and severity (Sarhadi et al. 2018; Wu et al. 2021). Despite numerous research on individual heatwave or drought, studies on the quantification of combined heatwaves and droughts occurrence and their trends in Australia are limited.

To fill the current knowledge gap, as mentioned above, the occurrence of CHDs in southeast Australia and their trend are investigated in this study over the period 1971–2021 during the extended summer season (November–March). The objective of this study is to quantify the spatiotemporal changes in CHD, focussing on recent changes in the occurrence of CHDs and their indices compared to the earlier period of the study period. The results of this study provide valuable input into health, water, forest and urban planning in southeast Australia.

2 Study area and data

The study focusses on southeast Australia, where drastic bushfires frequently take place (Clarke and Evans 2019). The area comprises the whole of Victoria, New South Wales (NSW) and the winegrowing portions of both Queensland and South Australia (SA) and is bounded by latitudes 25.96°S–39.17°S and longitudes 133°E–153.65°E. More than 57.9% of total population in Australia reside in this region.

Also, six of the seven longest rivers in Australia are located in the Murray-Darling Basin. This river system has maintained unique, diverse ecosystems and human life for tens of thousands of years. This basin covers a portion of SA, Victoria, the Australian Capital Territory, NSW and Queensland, just over 1 million km², or about one-seventh of the landmass of the continent (Fig. 1) and provides a third of Australia's food. Parts of the Darling and other major rivers are running completely dry with increasing frequency, indicating an alarming trajectory: the Murray-Darling Basin is dying. Hence, we focussed on choosing this part of Australia as the study area.

Fig. 1 Map of Murray-Darling Basin (Maclean et al. 2012)
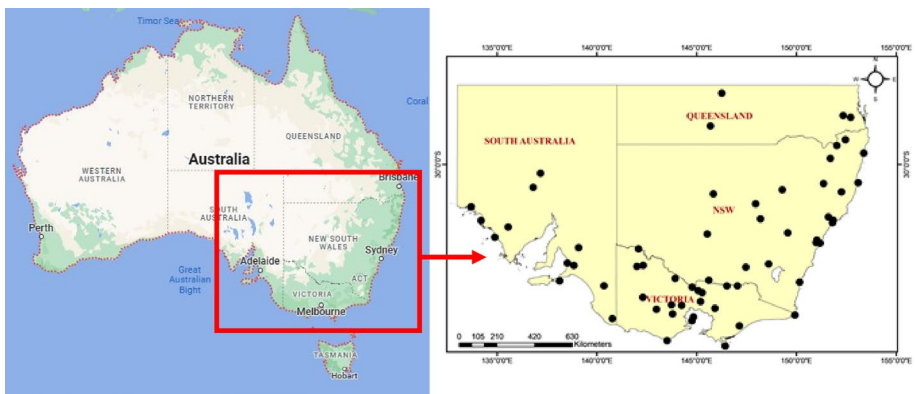

Fig. 2 Study area and locations of the selected weather stations

The study area (Fig. 2) has a total of 61 weather stations located in NSW (24), Victoria (21), Queensland (4) and SA (12), and the data are examined between 1971 and 2021 time period. These 61 weather stations are selected after screening the data, and their missing percentage was less than 5%. A spatial interpolation technique was used between the stations located within a 30 km radius to fill the missing data of the selected stations to have a continuous time series for each of the selected stations. The daily precipitation

and temperature data were collected from the Australian Bureau of Meteorology covering 1971–2021.

3 Methodology

3.1 Heatwave

The definition of heatwave varies, and there is no commonly accepted definition globally. However, in general, when the temperature exceeds any pre-defined threshold value for a number of consecutive days, it is considered as a heatwave event. In Australia, heatwave definition based on excess heat factor (EHF) value is recommended by researchers to investigate heatwave characteristics (Nairn & Fawcett 2013; Perkins & Alexander 2013).

In this study, a heatwave is considered when at least three consecutive days have EHF values greater than zero (EHF > 0 °C^2).

3.2 Drought

The standardised precipitation index (SPI) is considered to define and monitor droughts based on the precipitation (McKee et al. 1993). SPI is calculated based on the transformation of the cumulative precipitation over a specified period. SPI has been utilised in numerous drought studies and is also recommended by World Meteorological Organization (WMO) to monitor the drought (Hayes et al. 2011; Loukas et al. 2008; Khan et al. 2021). Therefore, in this study, SPI is used to identify the droughts in southeast Australia.

Although temperature, precipitation and soil moisture are key drivers for droughts, the calculation of SPI is only based on precipitation. Thus, it is dubiously assumed that droughts are only driven by precipitation (Mishra and Singh 2010; Vicente-Serrano et al. 2010; Yildirim and Rahman 2022b). Despite solid theoretical background and robust calculation method, SPI lacks to include other important factors in identifying droughts. Therefore, a modified drought index based on the temperature and precipitation was introduced called standardised precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010).

SPEI is calculated for a given month following the same principle based on the difference between accumulated monthly precipitation and potential evapotranspiration (PET). Consequently, SPEI represents drought more persuasively and has been used to identify drought characteristics globally (Beguería et al. 2014).

Table 1 Dry or wet conditions based on SPI and SPEI values

Values	Moisture levels
$+2.0$ and greater	Extremely wet
$+1.5$ to $+1.99$	Very wet
$+1.0$ to $+1.49$	Moderately wet
-0.99 to $+0.99$	Average
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Very dry
-2.0 and less	Extremely dry

SPI and SPEI can be estimated for different timescales as a result of the flexible calculation procedure, which permits these indices to be adopted for identifying short-, medium- and long-term droughts.

In this study, SPI and SPEI are calculated using the SPEI R package, where accumulated precipitation of different time series is fitted into gamma and log–log distributions, respectively. These probability distributions are then transformed into a normal distribution. Therefore, it is possible to compare the calculated SPI and SPEI spatiotemporally as the distributions are normalised. Three- and twelve-month SPI and SPEI are considered in this study to cover short- to long-term droughts.

Dry or wet conditions can be classified based on SPI or SPEI values, as summarised in Table 1 (McKee et al. 1993; Vicente-Serrano et al. 2010). In the present study, a drought period is defined as a set of months that have consecutively the SPI or SPEI thresholds of 0, −0.5 and −1.0.

3.3 Combined heatwaves and droughts (CHD)

In this study, at first, the spatio-temporal occurrence of heatwaves and droughts is identified individually according to methods described in previous sections for each of the selected stations in southeast Australia. CHD is considered to take place if both heatwaves and droughts occur on the same day for the same station (Ridder et al. 2021; Zscheischler et al. 2020).

Therefore, time series of independent occurrences of heatwaves and droughts are overlapped to identify the occurrence of CHD. However, heatwaves are identified on a daily scale, whereas drought indices (SPI and SPEI) are identified on a monthly scale. In this context, EHF values representing the heatwaves are calculated first for the study period. Thereafter, monthly drought indices are calculated and assigned to each day of the corresponding month. For example, if SPI or SPEI value for any station in November 2001 is −0.5, each day in November is considered to have the SPI or SPEI value of −0.5. Consequently, monthly time series of drought indices can be transformed into daily time series and, therefore, these easily overlap with daily time series of heatwaves occurrence.

CHD is considered to be occurred on any given day for any particular station, if both the EHF and drought index (SPI or SPEI) exceed the respective threshold values. In this study, we consider heatwave occurrence if the positive value of EHF sustains for at least three continuous days. However, to identify drought occurrence, three different levels of dryness are considered in this study, e.g. SPI or SPEI value less than 0, −0.5, −1.0. Although the value of drought indices less than 0 and higher than −1.0 does not indicate drought condition, these thresholds are considered as heatwaves in dry conditions may worsen the impacts on environment and humans.

In this study, CHD is identified for the extended summer season (November–March) for the period 1971–2000 and 2001–2021. The motivation behind the selection of two time periods is to compare the change in the recent occurrence of CHD compared to the earlier period.

3.4 Hotspot (total count and 90th percentile)

Hotspots for CHD are referred to as regions with a high frequency of concurrent heatwaves and droughts. In this context, the total number of days satisfying the criteria for both heatwaves and droughts simultaneously over the periods 1971–2000 and 2001–2021 at each

Table 2 Definitions of CHD indices

CHD indices	Definition	Unit
CHDN	Total number of CHD days in extended summer season of hydrological year	Days/season
CHDD	Duration of the longest CHD event in extended summer season of hydrological year	Days/season
CHDS	Accumulation of magnitude of all CHD events in extended summer season of hydrological year	°C²/season
CHDA	Maximum magnitude of all CHD events in extended summer season of hydrological year	°C²/season

selected station is counted. For the purpose of identification of hotspot of CHD over southeast Australia, annual frequency of CHD is also calculated and 90th percentiles of annual frequency of CHD over the time periods of 1971–2000 and 2001–2021 are calculated for each selected station.

Kriging is adopted as the spatial interpolation technique to prepare the hotspot map of CHD for southeast Australia.

3.5 CHD characteristics and their trends

In this study, trends in the frequency, duration, severity and amplitude of CHD are investigated. The definitions of these four indices of CHD are summarised in Table 2 (Mukherjee & Mishra 2021; Reddy et al. 2022).

Magnitude of CHD is calculated by Eq. (1):

$$CHDM = -Drought\ index \times EHF\,°C^2 \qquad (1)$$

Mann–Kendall (MK) test followed by Theil–Sen slope (Sen 1968) calculation is adopted in this study to detect the trend in the CHD indices and their significance at 95% confidence level over the earlier period (1971–2000) and recent period (2001–2021).

4 Results

4.1 Compound heatwaves and droughts (CHD) hotspots

The spatial distribution and change in the CHD hotspots were assessed in this study, and for this purpose, the total study period 1971–2021 was divided into two periods, i.e. 1971–2000 and 2001–2021. The CHD hotspot was identified based on the total count and 90th percentile of the CHD days that occurred during the extended summer seasons for the selected two periods.

4.1.1 Total count

CHD occurred throughout southeast Australia, with a stronger signal in the eastern side of the study area. CHD hotspots considering SPEI3 and SPEI12 are shown in Figs. 3 and 4.

In the period 1971–2000, the CHD hotspots were concentrated mostly in the eastern side of NSW and Queensland states of Australia. In the last two decades, the hotspot extended spatially towards the west region of southeast Australia. Considering SPEI values less than 0, -0.5 and -1.0 for identifying drought conditions, it is also observed that the central NSW was more prone to CHD with the drier condition. For area average, the average annual CHDs occurring in 2001–2021 were about 89, 78 and 77% higher than in the time period 1971–2000, for SPEI3 < 0, SPEI3 < -0.5 and SPEI3 < -1.0, respectively.

In the case of SPEI12, the increase in average annual CHDs was lower and observed to be 77, 71 and 63%, for SPEI12 < 0, SPEI12 < -0.5 and SPEI12 < -1.0, respectively. Although the total counts of the CHD were substantially less than SPEI3 in both time periods, the spatial distribution pattern of CHD considering SPEI12 was similar to SPEI3.

In this study, CHD, occurred in southeast Australia, is also calculated using the SPI3 and SPI12 as drought indices, as shown in Figs. 5 and 6. In the case of SPI as drought
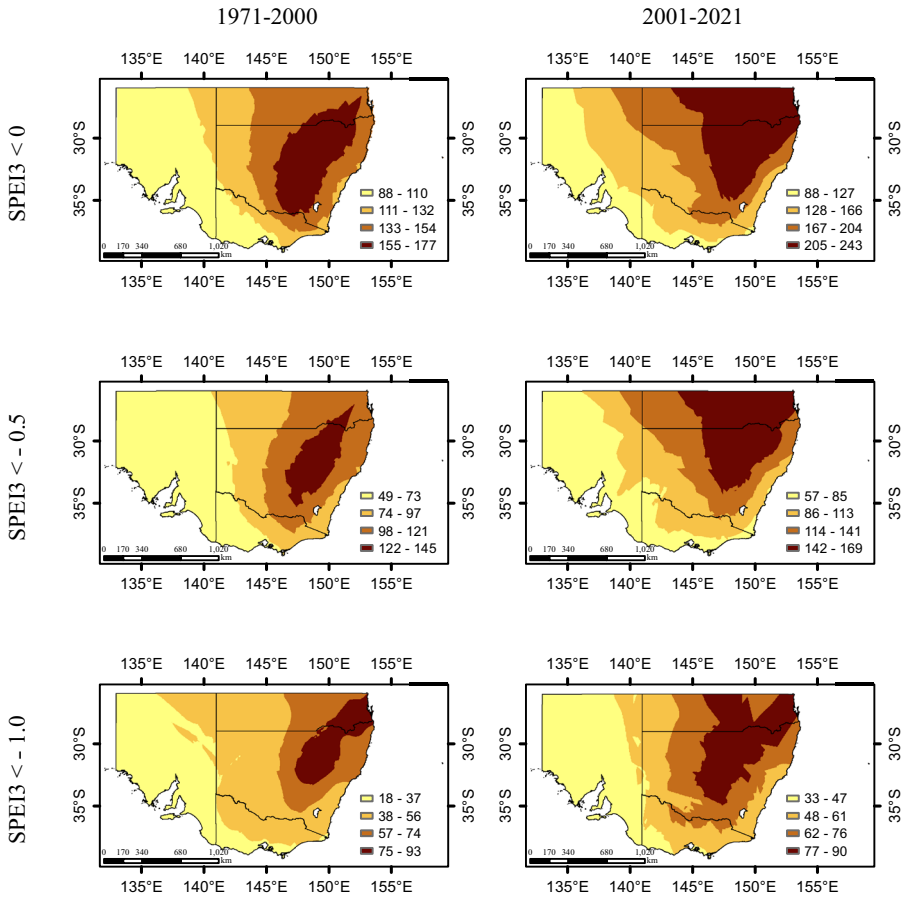
Fig. 3 Total count of CHDs considering SPEI3 as drought index

index, the spatial distribution of CDHs was also similar to the case of SPEI. However, the total count was less than the corresponding SPEI cases, which was more pronounced with drier conditions. Similar to SPEI, in cases of SPI, the average annual CHDs, averaged over the study area, occurred in 2001–2021 were substantially higher than in the time period 1971–2000. This increase was observed in the range of 52–92% for all the SPI cases.

It is also worth noting that the hotspots moved towards central NSW and the southeast region of Queensland for SPEI and SPI indices, respectively, with drier conditions.

4.1.2 90th percentile

Figures 7, 8, 9 and 10 represent the CHD hotspot considering 90th percentile of the seasonal number of CHD days. 90th percentiles of seasonal CHD days were considered to identify the extreme compound heatwaves and droughts in the period 1971–2000 and 2001–2021 for southeast Australia. No significant difference was identified between the spatial distribution of CHD considering the total count and 90th percentile of CHD.
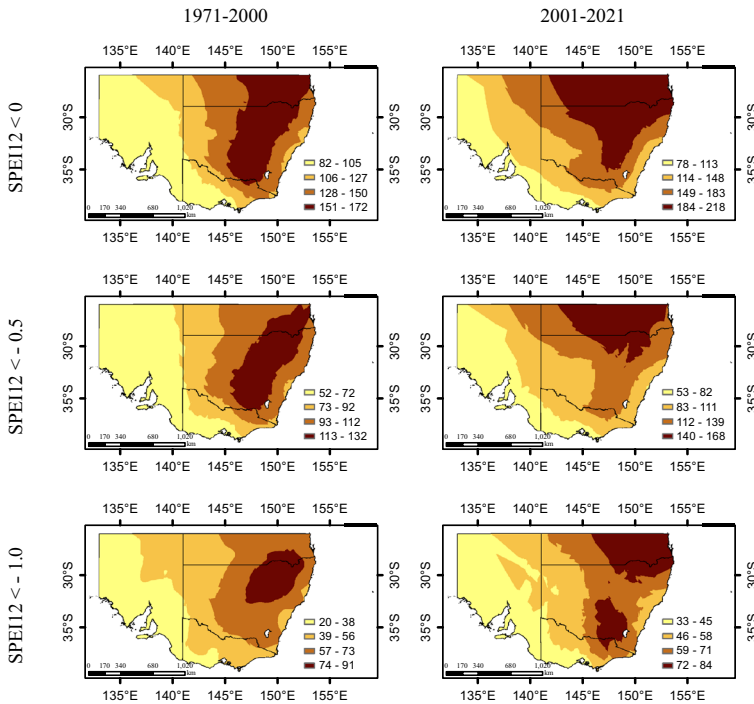
Fig. 4 Total count of CHDs considering SPEI12 as drought index

The increase in the area averaged 90th percentile of CHD between the earlier cooler period (1971–2000) and recent warmer period (2001–2021) was found to be 51, 46 and 65% for SPEI3 < 0, SPEI3 < 0.5 and SPEI3 < −1.0, respectively. These increases in 90th percentiles of CHDs were 56, 59 and 62%, for SPEI12 < 0, SPEI12 < 0.5 and SPEI12 < −1.0, respectively. Similarly, in case of SPI, these increases were in the range of 54–65%.

The global hotspots for combined heatwave and drought for time period 1980–2014 were examined by Ridder et al. (2020), Ukkola et al. (2018) and Pitman, et al. (2022) and noted that the return periods were less than 1 year for most of the region of Australia and less than 0.5 year for eastern region of Australia. In the analysis, they considered threshold values SPI3 ≤ −1.3 and EHF > 0 for drought and heatwave identification, respectively. However, in our study, return periods increased (up to 4 years in southeast Australia). Similar spatial pattern of CHD hotspots was observed in our study considering both SPI and SPEI for recent time period (2001–2021) as shown in Figs. 3, 4, 5, 6, 7, 8, 9 and 10.

4.2 Trends in CHD indices

In this study, the trends in different CHD indices during two periods 1971–2000 and 2001–2021 are calculated and shown in Figs. 11, 12, 13, 14, 15, 16, 17 and 18. For each CHD index, both SPEI and SPI drought indices are used with three threshold levels, i.e. less than 0, −0.5 and −1.0. However, considering threshold value −1.0 for SPEI and SPI
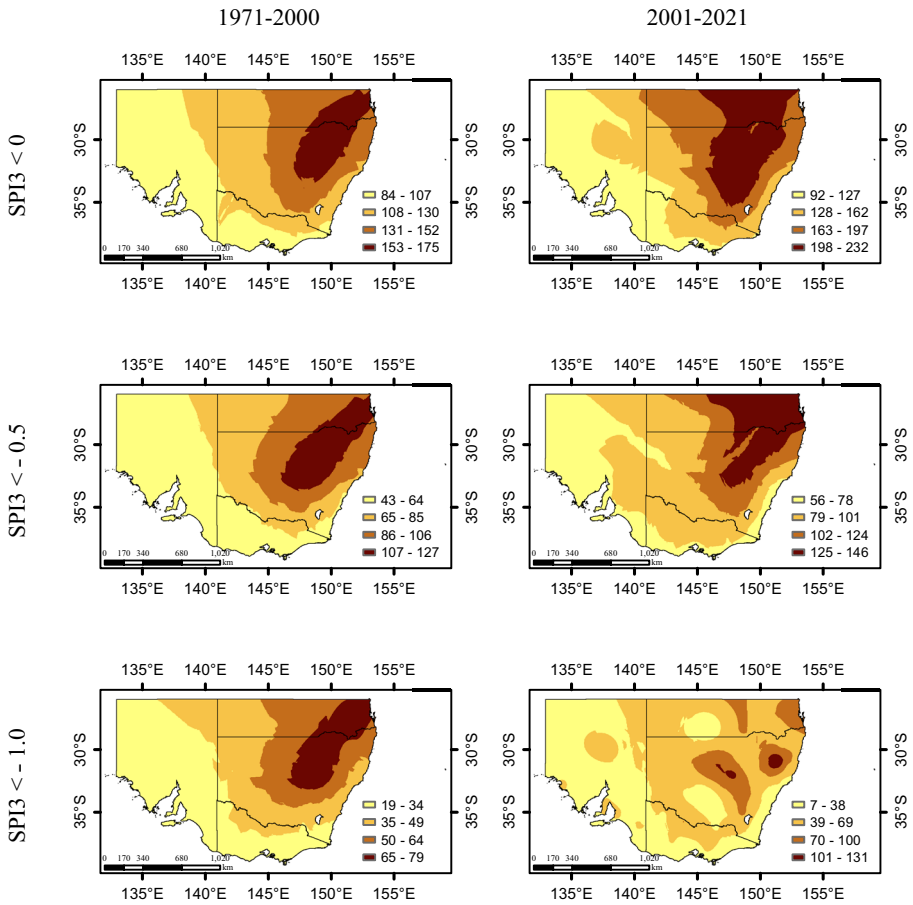
Fig. 5 Total count of CHDs considering SPI3 as drought index

indices yielded fewer CHD events, and no trend was found for any cases. Therefore, results considering thresholds 0 and −0.5 are presented in this paper.

4.2.1 CHDA (Maximum magnitude reached by the intense CHD event on a particular day in a season)

In general, no trend in CHDA during the period 1971–2000 was found, irrespective of the drought index selection and threshold value, as shown in Figs. 11 and 12. Except in the case of SPEI3 with threshold value 0, only two stations (Mount Barker and Keith) located in SA within the study area and one station named Maryborough in Victoria showed significant positive and negative trends, respectively.

On the contrary, in the recent period of 2001–2021, 29 (out of 61 stations i.e. 47.5%) and 23 (39%) stations experienced an upward trend at 5% significance level for 3-month SPEI and SPI, respectively, whereas for 12 months, both indices showed an increasing
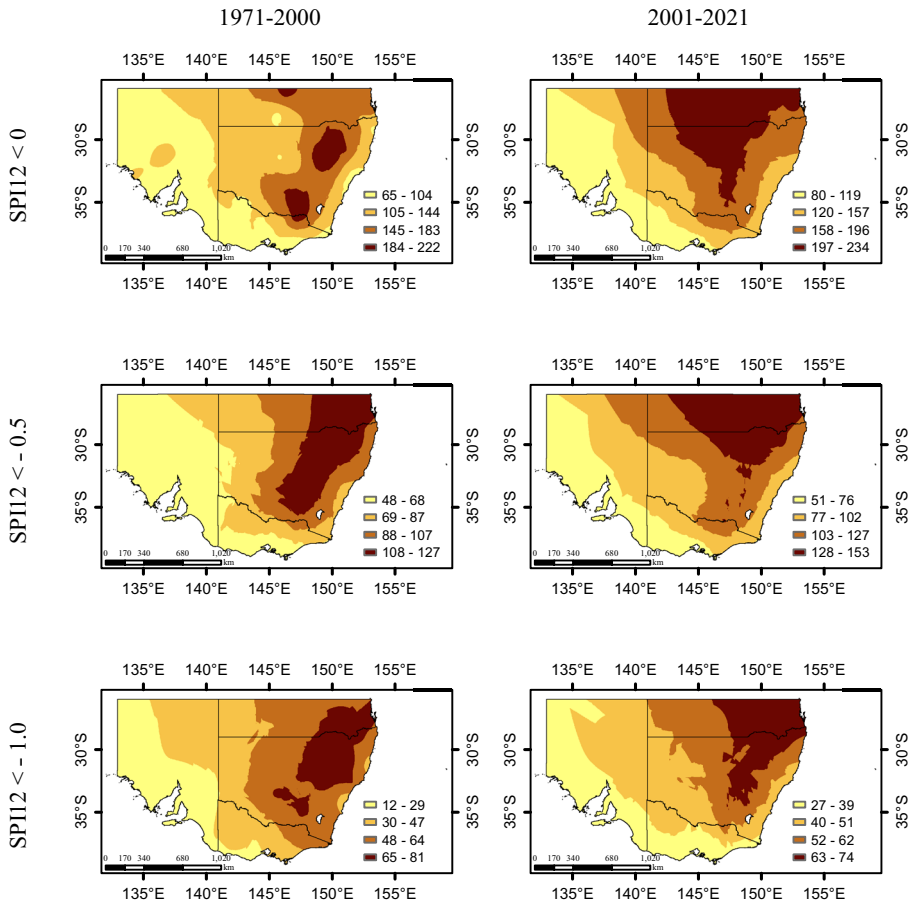
Fig. 6 Total count of CHDs considering SPI12 as drought index

trend in 24 (39%) and 10 (16.4%) stations. The rate of increasing trend ranged between 0.04 − 3.37 °C^2/season and 0.06–0.99 °C^2/season for SPI3 < 0 and SPI12 < 0, respectively. Thus, the range was greater for 3 months compared to 12 months. For SPEI3 < 0 and SPEI12 < 0, these ranges were found to be higher (0.01–3.46 °C^2/season and 0.02–1.79 °C^2/season, respectively) compared to SPI. Most of the stations, which indicate the higher values of CHDA, are located in NSW and Victoria.

The number of stations showing increasing trends substantially dropped with a threshold value − 0.5 for both SPEI and SPI drought indices. For SPEI3 and SPI3, 8 and 2 stations showed increasing trends with threshold value − 0.5, respectively, and only one station showed a positive trend in the case of both indices with 12 months. Thus, the increment was greater for threshold value 0 than − 0.5.

However, CHDA using the lower drought threshold (SPI3 < − 0.5) showed more widespread positive changes than using the stricter threshold of moderate drought (SPI3 < − 1), which agrees with the findings by Reddy et al. (2022). As per Reddy et al. (2022), the changes in amplitude of CHD between periods 1958/59-1988/89 and 1989/90-2019/20
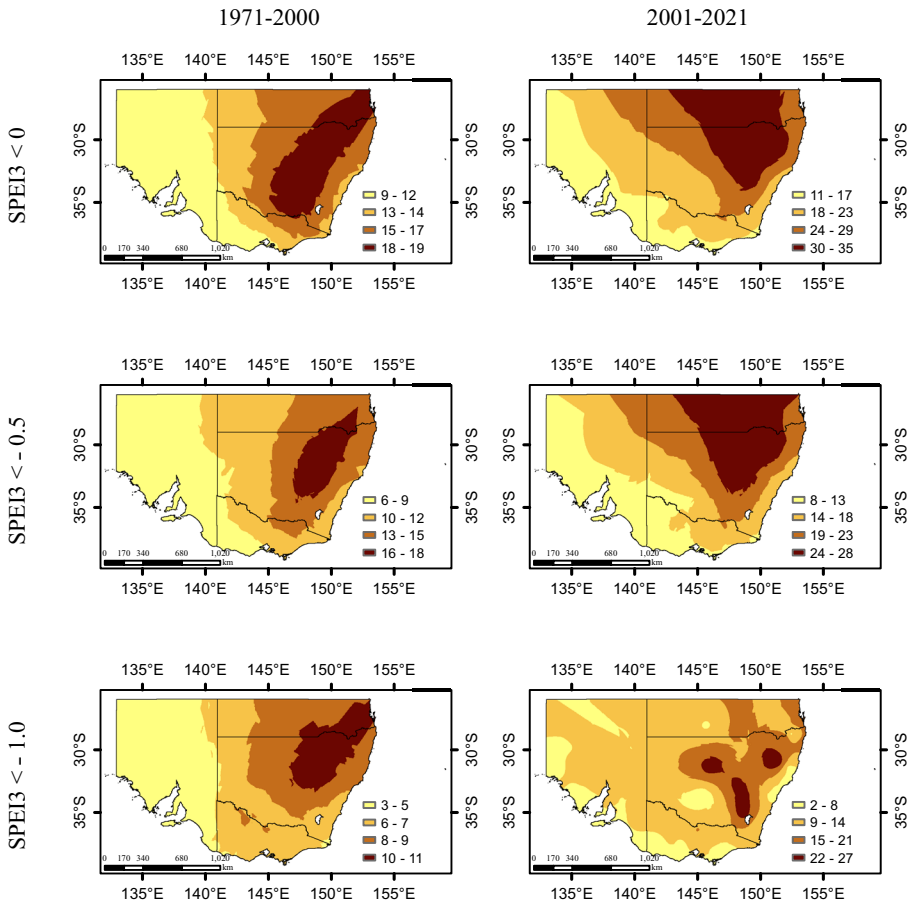
Fig. 7 90th percentile of CHDs considering SPEI3 as drought index

were up to 13.5 °C²/season at the stations located in the parts of Queensland, North East portion of NSW and near south coastal regions of Victoria and negative changes in the middle of NSW. In our study, the changes in amplitude of CHD between periods 1971–2000 and 2001–2021 were up to 49 °C²/season at the stations located in the parts of Queensland, North East portion of NSW and near south coastal regions of Victoria and negative changes at one station in the middle of NSW (Figure S1).

4.2.2 CHDD (duration of the longest CHD event in a season)

Trends in CHDD during 1971–2000 and 2001–2021 for both SPI and SPEI indices are shown in Figs. 13 and 14. Generally, no trend in CHDD during the period 1971–2000 was found, irrespective of the drought index selection and threshold value. In cases of SPI3 and SPEI3 with threshold value 0, only one station showed a decreasing trend in Victoria.
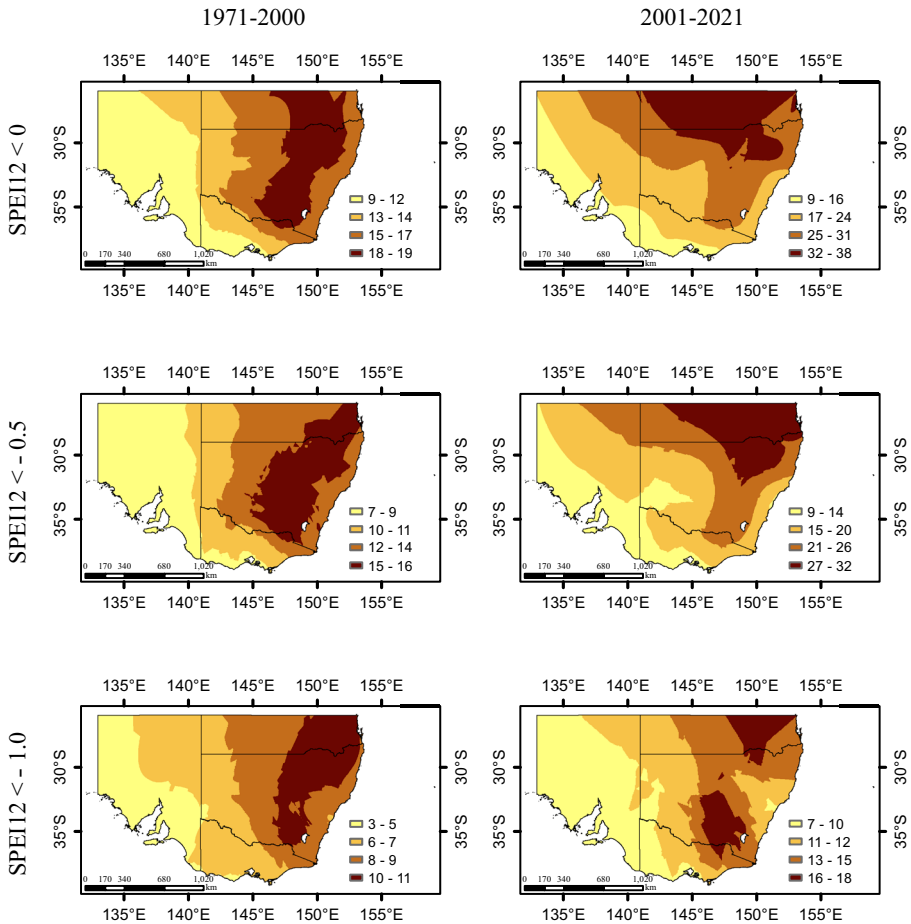
Fig. 8 90th percentile of CHDs considering SPEI12 as drought index

At the 5% significance level for 2001–2021 period, the MK test result showed that 14 and 10 stations out of 61 stations, i.e. 23 and 16% of stations, exhibited positive trends while considering 3 months for both indices. Only six stations showed positive trends for 12 months of SPEI < 0 and SPI < 0.

CHDD based on SPI3 is of shorter duration compared to SPEI3 for most of the region, and the values ranged between 0.03–0.41 days/season and 0.03–0.52 days/season, respectively, and most of the stations are located in NSW and SA regions. Different patterns can be observed for 12-month SPEI with smaller CHDD (0.1–0.30 days/season) compared to SPI (0.07–0.41 days/season) and most of the stations located in the NSW region.

Similar to CHDA, the number of stations showing increasing trends substantially dropped with a threshold value of −0.5 for both SPEI and SPI drought indices. Only five and one stations showed an upward trend ranging between 0.03–0.33 days/season and 0.25 days/season, in cases of SPEI3 and SPI3, respectively. For SPEI12, only four stations showed an upward trend, and no station showed any trend for the SPI indices.
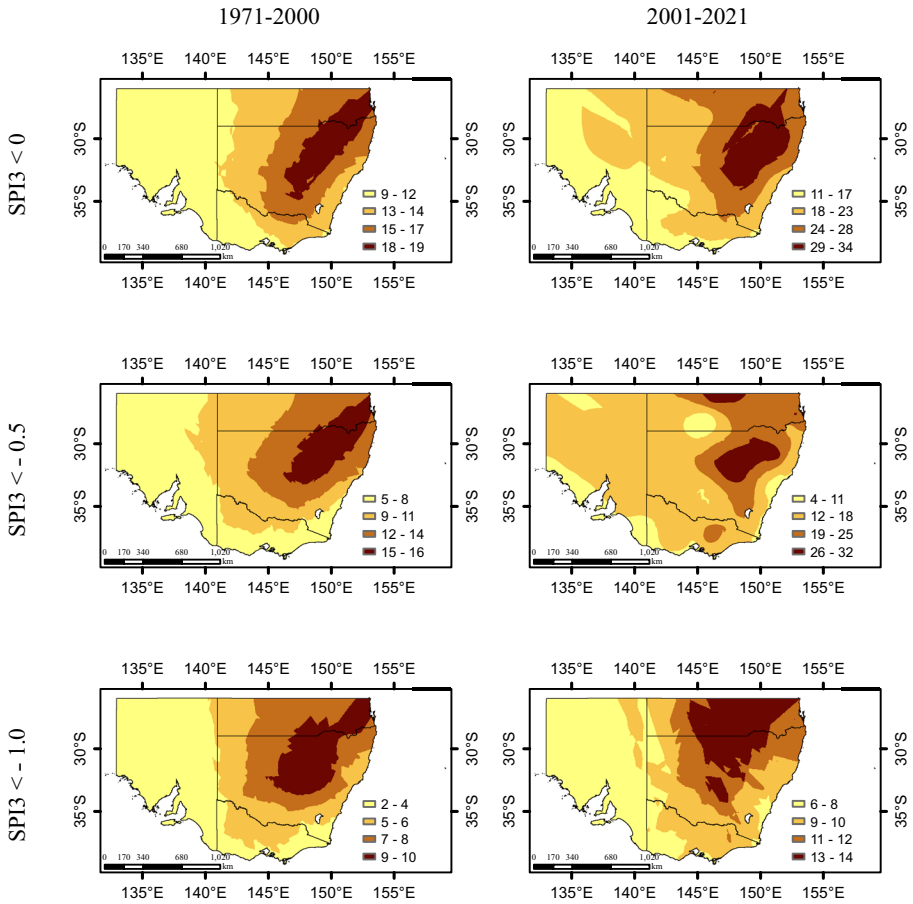
Fig. 9 90th percentile of CHDs considering SPI3 as drought index

Reddy et al. (2022) found the change in duration of CHD up to maximum 2 days/season with changes around 0 days towards south end of southeast Australia; we found similar spatial pattern with maximum 4 days/season increase in duration (Figure S1).

4.2.3 CHDN (total number of CHD days in a season)

Figures 15 and 16 show trends in the total number of CHD days in a season for both SPEI and SPI drought indices. At seasonal timescales, all the stations exhibited no trends for SPI and SPEI in the 1971–2000 time period, with the exception of SPEI3 < 0. In this case, only one station showed a statistically significant upward trend in the SA region. On the other hand, a greater number (23 out of 61 stations, e.g. 38%) of stations exhibited a positive trend and measured 0.03–0.88 days/season for the 2001–2021 study period. Most of these stations are located in the NSW region. An upward trend also persisted in the coastal region of SA.
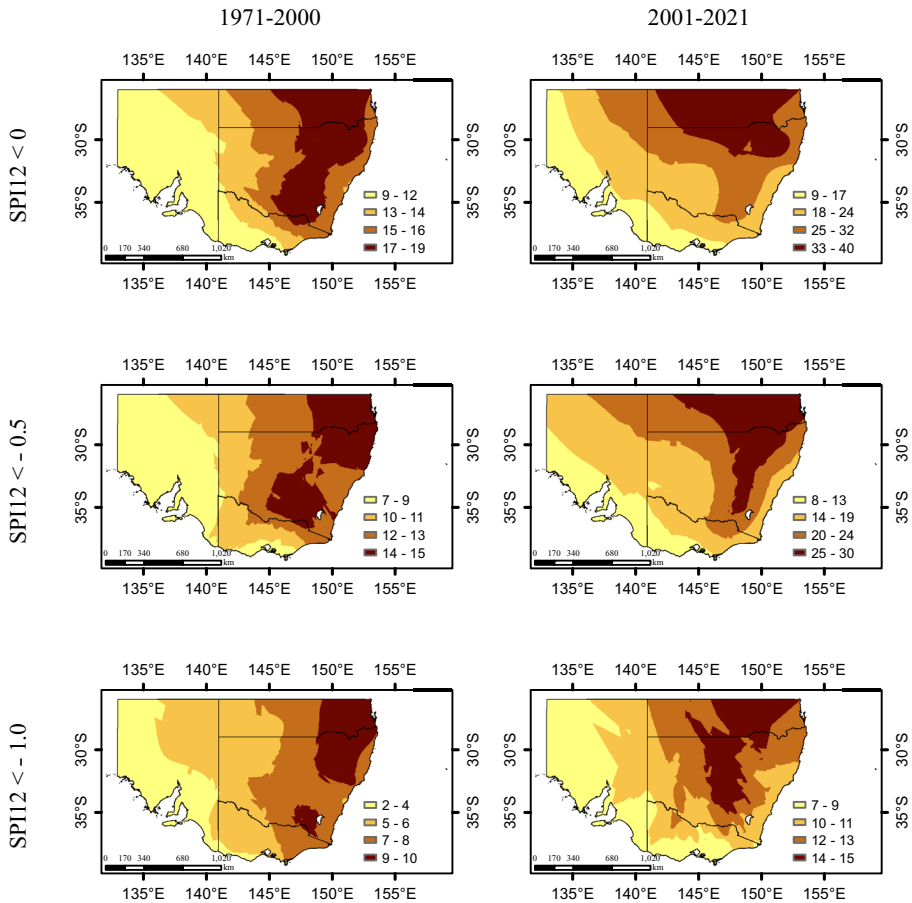
Fig. 10 90th percentile of CHDs considering SPI12 as drought index

Compared to SPEI3 < 0, the total number of CHD days increased was lesser for SPI3 < 0 (17 out of 61, i.e., 28%) in the recent period with a similar range of increment (0.03–0.86 days/season). SPEI12 and SPI12 tended to measure fewer events between 0.05–0.65 days/season and 0.05–0.79 days/season, respectively, with fewer stations, e.g., 11 and 13, respectively.

Similar to CHDA and CHDN, the number of stations showing increasing trends for the total number of CHD days substantially dropped with a threshold value −0.5 for both SPEI and SPI drought indices. Only six and two stations showed increasing trends with threshold value −0.5 for SPEI3 and SPI3 indices, respectively. In general, regional trends in the last two decades were larger in magnitude, which is at least in part due to greater overall warming of the global climate in later decades.

Also, the changes in frequency of CHD occurred in 1989/90–2019/20 compared to the period 1958/59-1988/89 were as large as 5 days/season and spatial distribution of the frequency changes was similar to the changes in duration of CHD (Reddy et al.
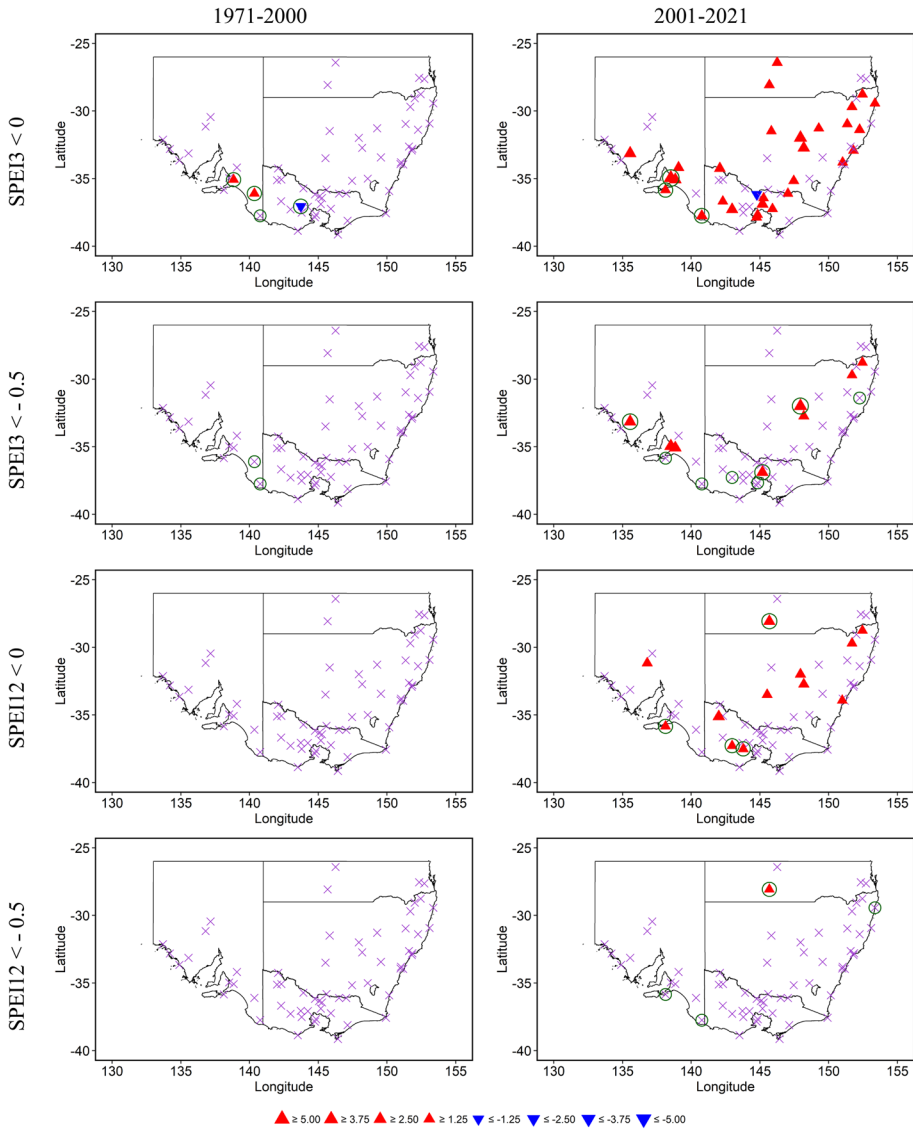
Fig. 11 Trends in CHDA considering drought index SPEI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level

2022). In our study, similar temporal and spatial patterns in the changes of frequency of CHD were also observed for both the study periods as shown in Figure S1.
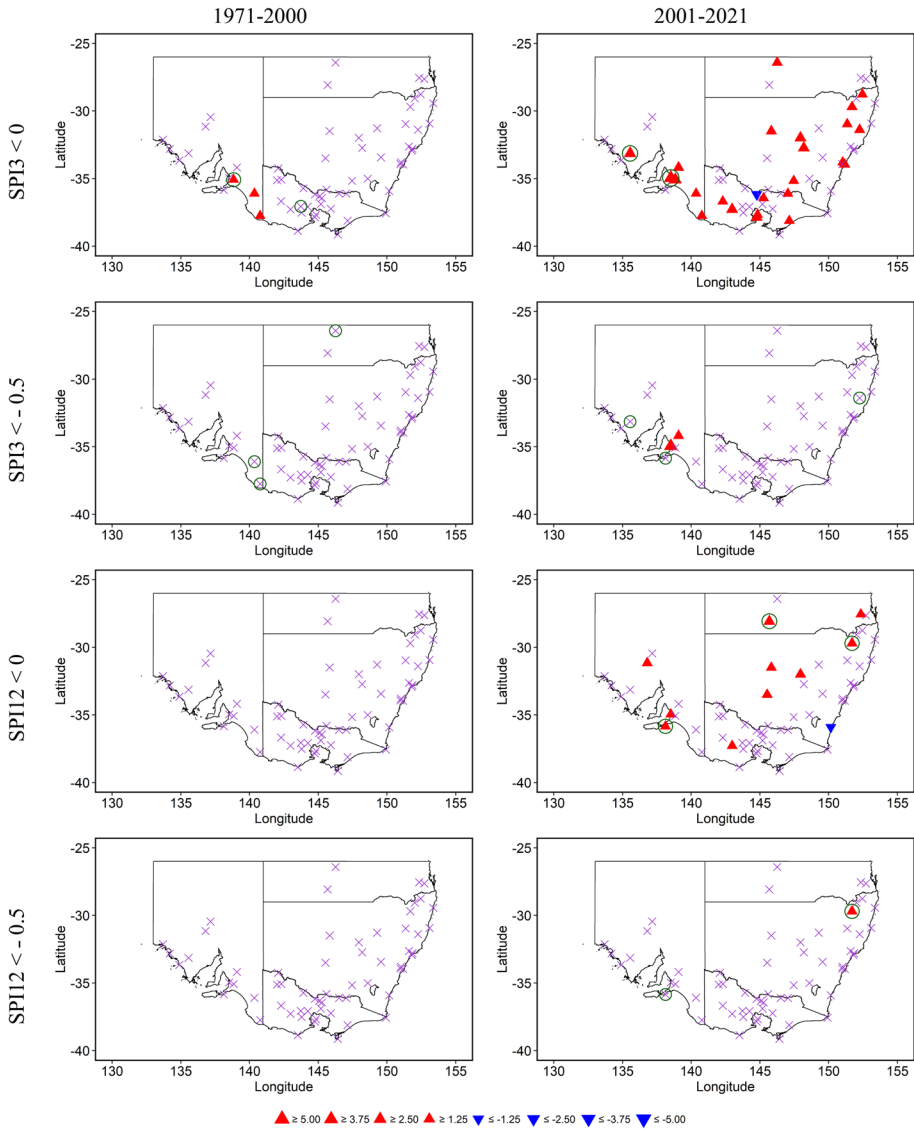
Fig. 12 Trends in CHDA considering drought index SPI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level

4.2.4 CHDS (the seasonal sum of magnitude across all CHD days)

Similar to other compound hot drought attributes, in general, no trend was observed for CHDs during the period 1971–2000, irrespective of the drought index selection and threshold value, as shown in Figs. 17 and 18. In cases of SPEI3 and SPI3 with threshold value 0, only one and two stations located in SA coastal region showed an increasing
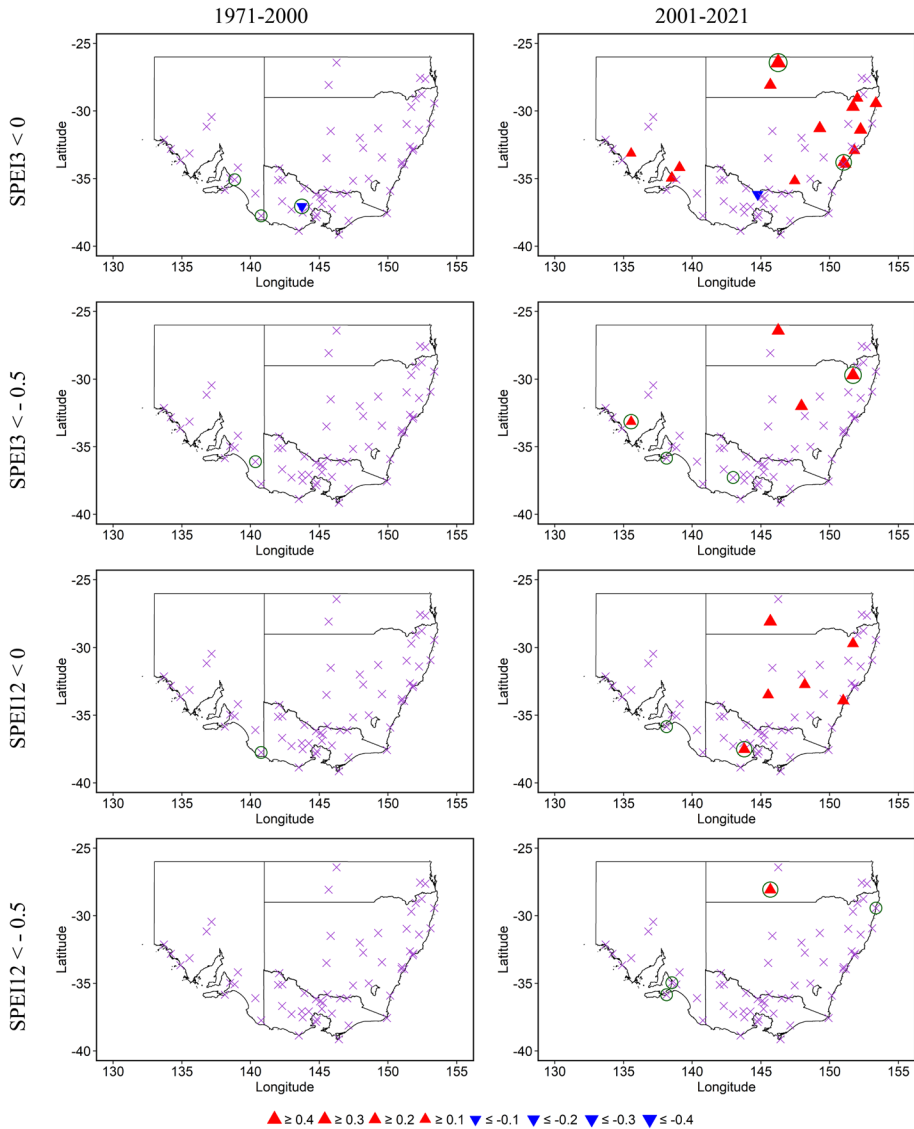
Fig. 13 Trends in CHDD considering drought index SPEI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level

trend, respectively. Two and one stations out of 61 selected stations for SPEI3 < 0 and SPI3 < 0 showed decreasing trend located in Victoria and SA states.

On the contrary, in the recent period of 2001–2021, 28 (out of 61 stations, i.e. 46%), 12 (20%), 24 (39%) and 12 (20%) stations showed an increasing trend for SPEI3, SPEI12, SPI3 and SPI12 with threshold value 0, respectively.
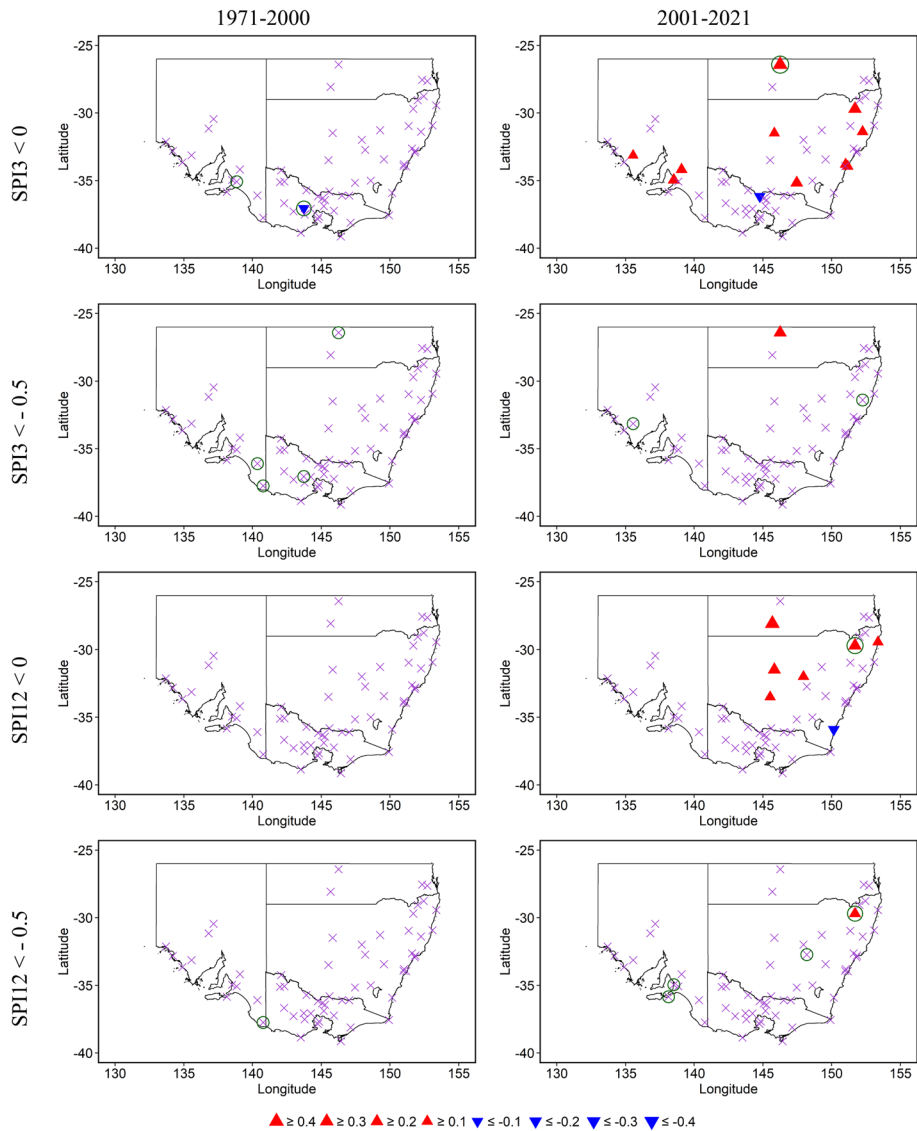
Fig. 14 Trends in CHDD considering drought index SPI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level

The rate of increasing trend varied from 0.03 to 8.66 and 0.13 to 9.07 °C^2/season for SPI3 < 0 and SPI12 < 0, respectively. For SPEI3 and SPEI12, these ranges increased to 0.00–9.38 °C^2/season and 0.02–12.10 °C^2/season, respectively. The number of stations showing increasing trends significantly dropped with threshold value −0.5 for both SPEI and SPI drought indices. Nine and three stations showed increasing trends with threshold value −0.5 for SPEI3 and SPI3 indices, respectively. However, CHDS
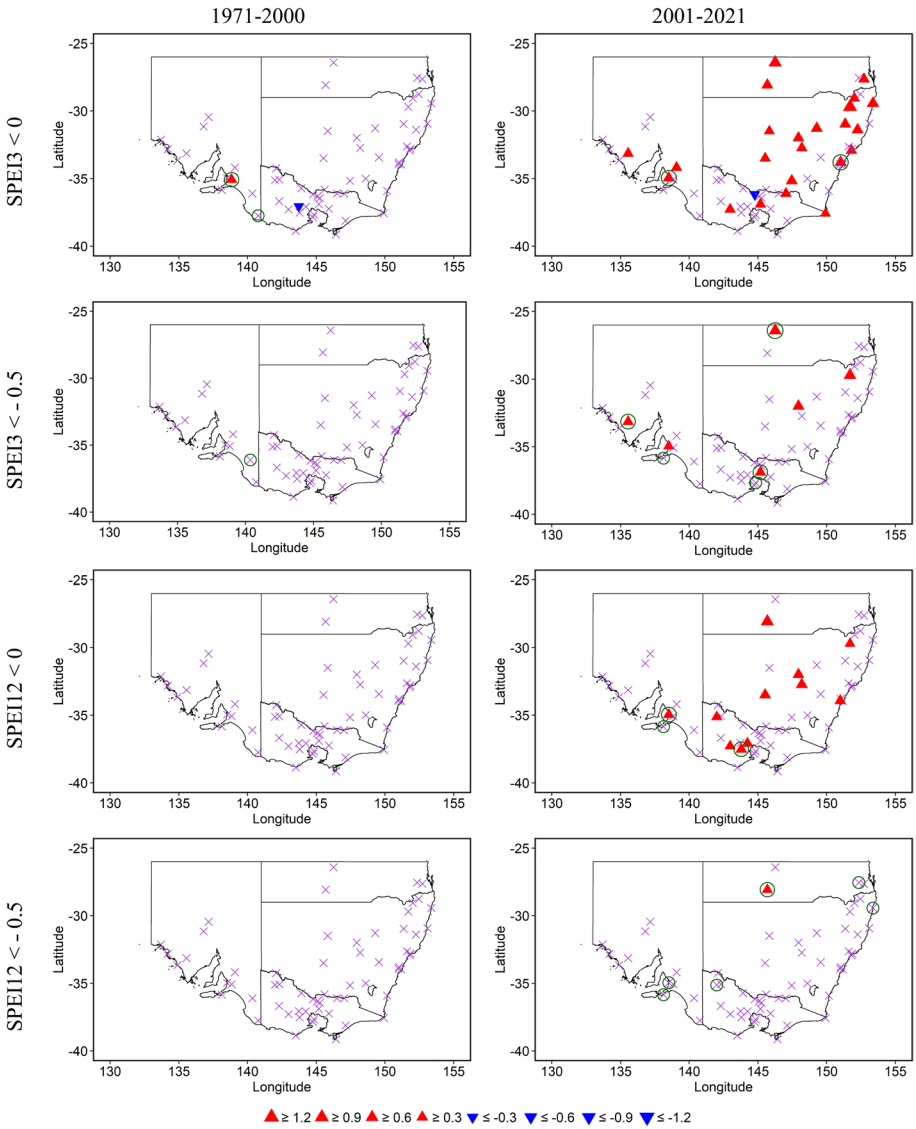
Fig. 15 Trends in CHDN considering drought index SPEI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level
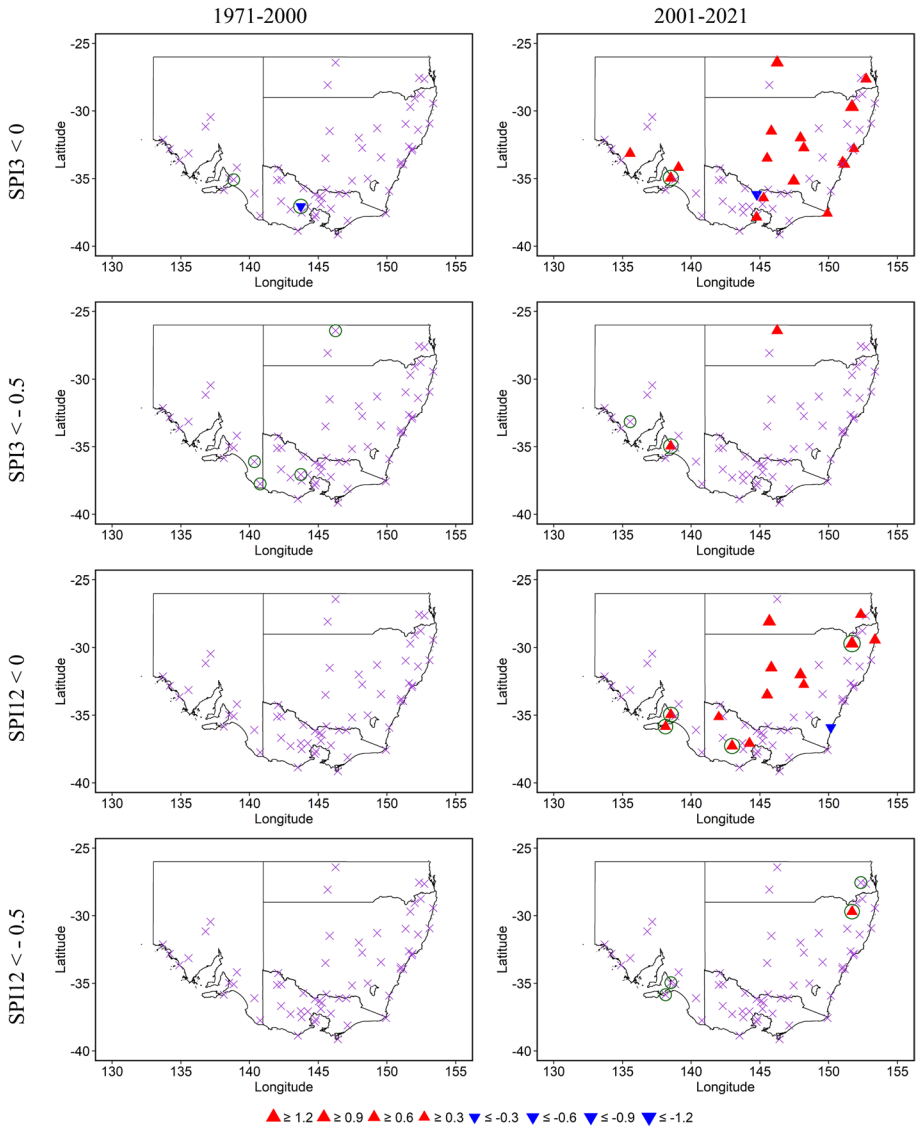
Fig. 16 Trends in CHDN considering drought index SPI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level
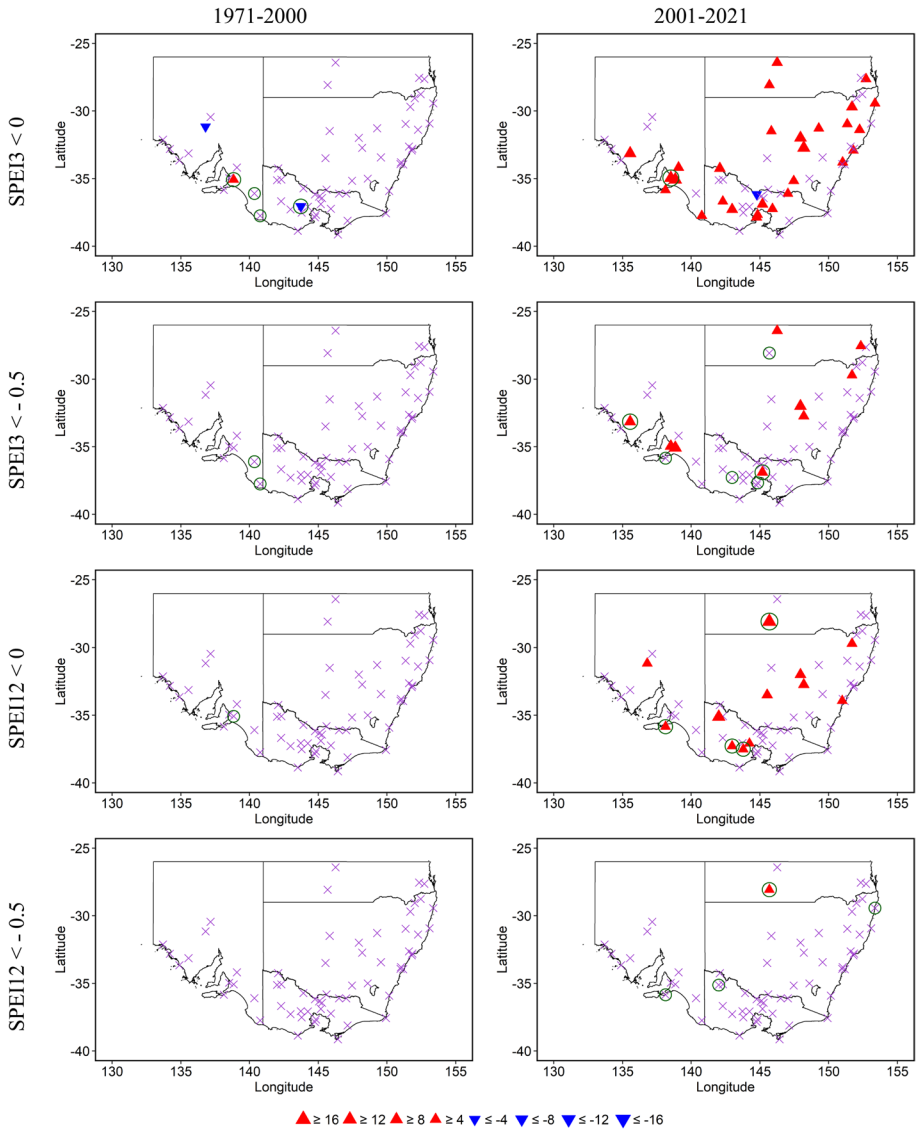
Fig. 17 Trends in CHDS considering drought index SPEI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level

Fig. 18 Trends in CHDS considering drought index SPI for time periods 1971–2000 and 2001–2021. Purple cross indicates no trend, and green circle indicates significant trend at 5% significance level
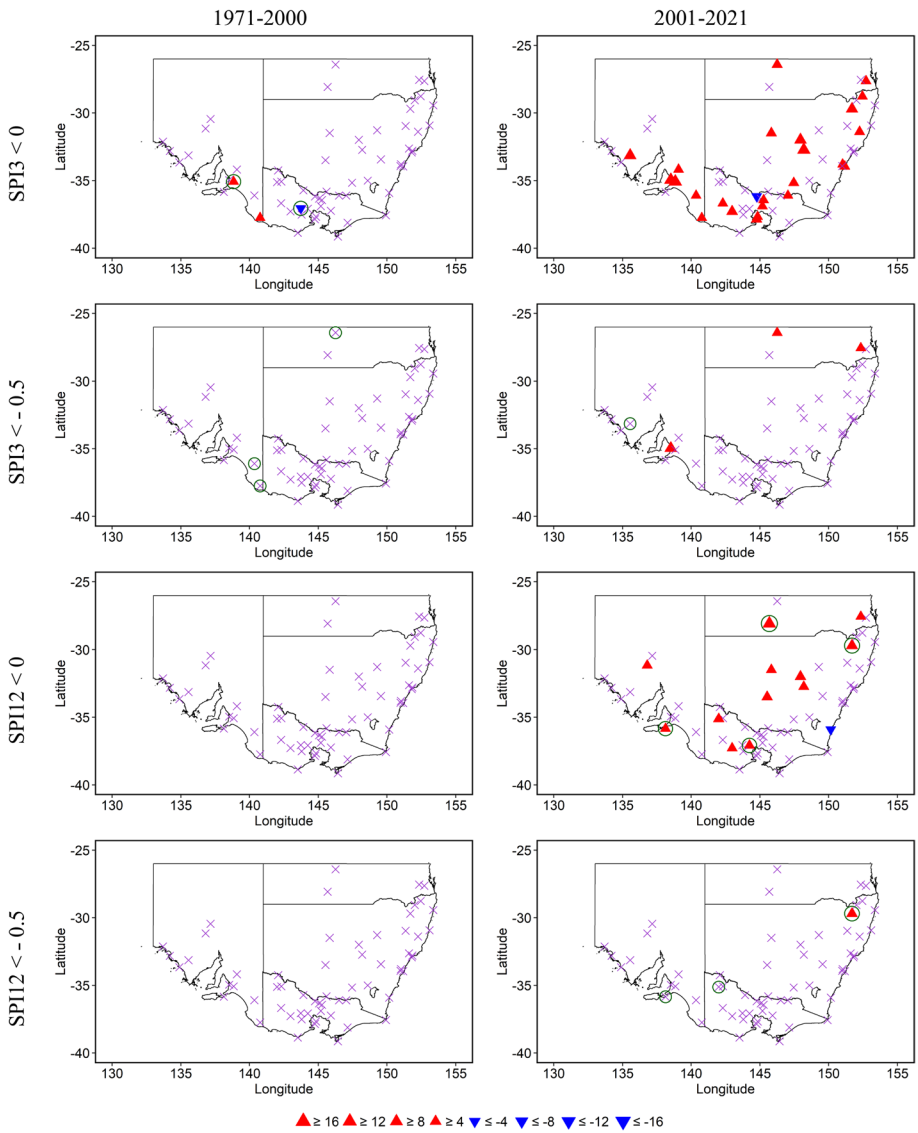
using the drought threshold value 0 showed more widespread positive changes in the CHDS metrics than the CHDS using the stricter threshold of moderate drought (SPI3,12 < − 0.5).

Changes in severity of CHD also exhibited similar patterns in case of the changes in amplitude of CHD in 1989/90–2019/20 with reference to the period 1958/59–1988/89 with a maximum value of 90 °C^2/season (Reddy et al. 2022). Although the pattern of the changes in severity of CHD in this study between two study periods was similar to Reddy et al. (2022), our observed changes were much higher with a maximum value of 156 °C^2/season (Figure S1).

5 Discussion

A rise in the occurrence of compound dry hazards is connected with the increase in temperature, which is worsened by global warming (Mazdiyasni and AghaKouchak 2015; Zscheischler et al. 2018). On a regional level, increases in the occurrence and amplitude of CHD are influenced by the anomalies in extreme mean temperature (Perkins and Lewis 2020). Individually, both heatwaves and droughts are affected by the surface flux (Shi et al. 2021a, b) and trigger each other implicitly (Dong et al. 2022; He et al. 2022).

The temperature and precipitation, directly and indirectly, influence heatwaves and droughts. Precipitation and temperature vary over Australia seasonally and spatially due to the large-scale climate indices, such as El Nino Southern Oscillation (ENSO), South Annular Mode (SAM), Indian Ocean Dipole (IOD) (Hao et al. 2018a; Mukherjee et al. 2020; Risbey et al. 2009). Not only large-scale teleconnections (Mukherjee et al. 2020) but also variations in soil moisture (Schwingshackl et al. 2017), magnitude and variability of seasonal precipitation and evaporation (Konapala et al. 2020) and the factors operating at regional scales (Herold et al. 2016) are influential factors for the regional variability of CHD events. Therefore, it is crucial to identify the regional and temporal variation of CHD in southeast Australia (Perkins et al. 2015).

In this paper, the hotspots of CHD in southeast Australia were identified, and a good degree of similarity was found in the spatial pattern of CHD hotspots compared to the regional and global results (Hao et al. 2018b; Ridder et al. 2020; Sharma & Mujumdar 2017; Vogel et al. 2021). This paper also predominantly focusses on the occurrence of combined heatwaves and droughts and trends in their characteristics, i.e. CHDN, CHDD, CHDS and CHDA in southeast Australia. Heatwaves are calculated based on the EHF values, and droughts are calculated based on SPI and SPEI values considering temperature and precipitation data over two periods (1971–2000 and 2001–2021).

In this study, results show that the arid region mainly experienced higher CHD events, in terms of magnitude and duration, compared to the coastal region of the study area. Mukherjee & Mishra (2021) also found that the increase in CHD events is mostly notable in the arid regions of the globe. Ridder et al. (2022a, b) reported that regional variability was quite noticeable for drought and heatwaves, and it was also prominent that the hotspots were emerging towards the inland region of the study area. Feng et al. (2020) also reported similar findings over the time period 1951 to 2012 on a global scale.

During 1971–2000, the changes in frequency and intensity of CHD in southeast Australia were much less spatially coherent compared with those during 2001–2021. A similar finding was reported by Mukherjee & Mishra (2021), who quantified the spatiotemporal variations in the CHD incidents at a global level based on a recent warmer period

(2000–2016) and a past period (1983–1999). They found that recent times have seen a marked increment in the frequency, duration and severity of CHD events. Mukherjee & Mishra (2021) also noted a similar trend over the world.

Ukkola et al. (2018) projected more frequent hot and dry compound events mainly due to the increase in the occurrence of heatwaves, even in the reduction of the drought frequency. Similar findings were also reported in China (Ye et al. 2019). It is also reported that the heatwaves in Australia, particularly in the southeast region, have been intensifying and are projected to be more intense under the current global warming situation (Reddy et al. 2021; Trancoso et al. 2020).

Previous results reported in the literature showed similar spatial patterns of hotspots of CHD with differences in magnitude and trends, despite considering different timescales, data sources and threshold values for identifying heatwaves and droughts. However, all the results highlighted the increased occurrence and intensity of CHD spatially and temporally.

Compound hazard events have been gradually attracting more attention. Therefore, it is crucial to explore the temporal and spatial characteristics of CHD not only on a global level but also on a regional level to evaluate their influence on health, agriculture and the ecosystem, as well as proper management plans.

6 Conclusions

This study identified current hotspots of compound heatwaves and droughts (CHD) and trends in their occurrences in southeast Australia. Results showed that CHDs occurred throughout southeast Australia, with higher concentrations on the eastern side of NSW and Queensland states. Also, the total count of CHD days increased significantly in the last two decades. In general, no trend was observed in CHD indices during the 1971–2000 period. However, in the recent period 2001–2021, significant trends were observed over the study area. These trends were particularly pronounced with 0 thresholds value for drought indices. The number of stations and magnitude of increasing trends reduced with threshold value of -0.5 and with higher aggregation of antecedent months. The outcome of this study highlighted the higher occurrence and increasing trends of CHD indices in the last two decades, which should be taken into consideration for the health and socio-economic management in the study area by the decision-makers.

Data availability The data used in this study can be obtained by contacting Australian Bureau of Meteorology (by paying a prescribed fee) (Australia's official weather forecasts & weather radar—Bureau of Meteorology (bom.gov.au)).

Declarations

Conflict of interest Authors declare that there is no conflict of interest to declare, and no funding was received to carry out this study.

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